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Research Article

Structural Analysis and Reinforcement Design of Sidewalk and Slab Elements in Composite Steel Bridges Based on SNI 1725:2016 and SAP2000 Simulation for Sustainable and Climate-Resilient Infrastructure

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Abstract

This research explores both the structural behavior and environmental relevance of sidewalk and deck slab components in composite steel-concrete bridge systems, emphasizing principles of sustainability and resilience to climate change. The focus was placed on the structural planning of the Palempay 5 Bridge, a Class A bridge located in West Kalimantan, Indonesia, which features reinforced concrete for both pedestrian pathways and vehicle lanes. The design follows key Indonesian standards, including SNI 1725:2016 for bridge loading, SNI T-12-2004 for concrete bridge structures, and SNI 2847:2013 for general concrete design. Using SAP2000, the bridge components were analyzed under multiple loading scenarios such as dead loads, live loads, pedestrian impact, and environmental factors like wind and thermal variation. The reinforcement was designed to maximize efficiency while ensuring structural integrity and durability. The analysis demonstrated that a sidewalk thickness of 50 cm and a deck slab thickness of 20 cm, reinforced with D16 and D13 bars, provided sufficient strength and serviceability. Furthermore, the bridge elements were shown to perform effectively under environmental stresses, aligning with climate-resilient design principles. This study contributes to the development of environmentally conscious infrastructure by combining optimized structural design with ecological considerations. It offers practical insight for civil engineers seeking to implement designs that reduce material consumption, lower carbon emissions, and enhance durability in the face of environmental change.

Keywoards: *Composite, SAP2000, Sustainable, Resilient Engineering, Reinforced*

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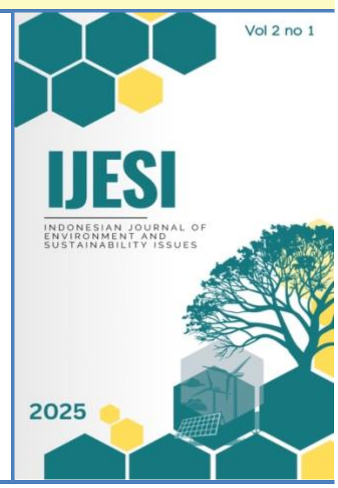

INTRODUCTION

Bridges serve as fundamental elements in transportation systems, functioning as connectors across natural and artificial barriers such as rivers, valleys, and highways [1], [2], [3]. They are essential for ensuring the smooth flow of people, goods, and services, while also supporting economic development and regional accessibility [4], [5], [6]. In the face of rapid urbanization and increased mobility needs, there is a growing demand for bridge structures that are not only robust and long-lasting but also environmentally responsible [7], [8], [9]. This development calls for modern engineering approaches that prioritize both structural integrity and ecological sustainability in infrastructure planning [10], [11]. Composite bridge systems, which typically integrate steel girders and reinforced concrete slabs, have become popular due to their efficient load distribution and construction flexibility [12], [13]. These structures utilize the tensile properties of steel and the compressive strength of concrete to withstand various types of loads, making them effective for supporting both vehicular and pedestrian traffic [14], [15], [16]. The addition of concrete sidewalks and deck slabs enhances durability while improving user safety and comfort [17], [18]. Nevertheless, designing these elements requires precise evaluation of diverse load combinations, including static loads, dynamic vehicle loads, and climatic factors such as wind pressure and temperature variation. Composite bridge systems, integrating concrete slabs over steel girders, are widely used due to their constructability, cost-effectiveness, and efficient load transfer. However, their performance in harsh tropical environments depends largely on precise detailing of deck and sidewalk slabs, which are often the most exposed and fatigue-prone elements. In this context, research into climate-responsive materials and structural optimization has gained traction. For instance, the use of Buton Rock Asphalt (BRA)-modified mixtures has been shown to significantly enhance the resilient modulus of pavement systems under low-frequency and high-temperature conditions—highlighting the importance of material behavior modeling in tropical infrastructure planning [19].

Indonesia's infrastructure expansion, particularly in remote and inter-provincial regions, continues to face logistical and environmental challenges. The Palempay 5 Bridge project, located in Melawi Regency on the route between Ella Hilir and Central Kalimantan, reflects these difficulties. As a composite steel-concrete bridge, it is expected to enhance connectivity while being resilient to environmental stressors prevalent in tropical zones. Therefore, its design must align with structural standards and simultaneously address sustainability issues such as material optimization, temperature-induced expansion, and long-term performance in fluctuating climatic conditions. Given the critical role of bridges in supporting mobility and development, it is increasingly important to ensure that their structural design meets not only safety and performance standards but also environmental sustainability objectives. The challenges posed by tropical climates—such as high humidity, temperature variation, and heavy rainfall can accelerate structural deterioration, increasing maintenance demands and reducing service life [20]. Moreover, excessive material consumption in bridge construction may lead to elevated greenhouse gas emissions and resource depletion, contradicting sustainable development principles. Accordingly, evaluating bridge components like sidewalks and slabs from both a structural and environmental perspective is essential to advancing climate-adaptive infrastructure. This study addresses those concerns by applying local design codes and simulation-based analysis to achieve structural reliability and sustainability goals.

Contemporary studies on sustainable bridge infrastructure have largely focused on enhancing structural efficiency, minimizing construction costs, and improving long-term durability, especially in developing economies [21], [22], [23]. Research has also explored landscape-sensitive bridge aesthetics, biophilic design integration, and education-based sustainability frameworks for civil structures [24], [25], [26]. Meanwhile, technological innovations such as long-span green bridges, advanced construction methods, and composite fiber materials have demonstrated positive outcomes in performance and environmental compatibility [24], [27], [28]. The adoption of eco-efficient materials including recycled aggregates and high-performance concrete along with life cycle assessment (LCA) frameworks, has been recognized as a crucial step in reducing environmental impacts [29]. Parallel to this, digital technologies such as digital twins, UAS inspections, and smart maintenance systems have been increasingly applied to enhance structural monitoring and climate resilience [30], [31], [32]. However, there remains a notable lack of research that integrates national structural codes specifically SNI 1725:2016 with simulation tools like SAP2000 for component-level analysis of sidewalks and deck slabs in composite bridges. Few studies consider environmental loads in tropical contexts where these components must endure elevated thermal stress and wind loads [33], [34]. This gap highlights the need for applied research that combines environmental resilience, national code compliance, and precise simulation in the micro-design of composite bridge elements.

This study aims to evaluate the structural behavior and reinforcement design of pedestrian sidewalks and deck slabs in a steel-concrete composite bridge using SAP2000, based on the requirements of SNI 1725:2016, SNI T-12-2004, and SNI 2847:2013. Additionally, the research seeks to analyze the environmental significance of the design by addressing material efficiency and adaptation to climate-related stress, supporting the development of sustainable, long-lasting bridge infrastructure in Indonesia.

METHODS

Research Design

This study was conducted using a quantitative-analytical approach, focusing on the assessment of both structural performance and environmental aspects of sidewalk and deck slab components within a composite steel–concrete bridge system. The methodology involved the integration of finite element-based simulation, national code compliance, and reinforcement calculation, taking the Palempay 5 Bridge as a case reference. This bridge, categorized as Class A, features a combination of concrete deck elements supported by steel trusses. The structural analysis was performed using SAP2000 version 22, where the slabs were idealized as plate elements forming part of a composite action. Loads applied in the model included self-weight (DL), additional permanent loads (SDL), moving loads from traffic and pedestrians (LL), as well as lateral and temperature-induced loads (WL and TL), all arranged according to combinations defined in SNI 1725:2016. The system was evaluated under both ultimate and serviceability limit states to ensure compliance with safety and usability requirements.

Reinforcement layouts were designed based on SNI T-12-2004 and SNI 2847:2013, which regulate concrete structures for bridges and general infrastructure respectively. Structural parameters analyzed included concrete compressive strength (f'c = 30 MPa), reinforcing steel yield strength (fy = 420 MPa), slab depth, and reinforcement types (D13 and D16 bars). SAP2000 simulation

outcomes—such as internal forces, slab deflection, and stress contours—were verified manually and used to guide detailing decisions. The design also considered material utilization to support environmental performance metrics.
Instrument

Time and Location
The study was executed over a five-month period, between March and July 2023. Analytical modeling and simulation were carried out at the Civil Engineering Laboratory of Politeknik Negeri Pontianak, using licensed academic software and technical documentation. Although this study did not involve physical field testing, it was grounded in a real infrastructure project: the Palempay 5 Bridge located in Melawi Regency, a strategic corridor linking Ella Hilir and the Central Kalimantan border. Dimensional and load-related data were acquired from preliminary design documents and national design guides, allowing for realistic modeling conditions.

Data Analysis
The data analysis process began with the creation of a digital model of the sidewalk and deck slab using SAP2000, configured to simulate real-world support conditions and load applications. Load cases were assigned according to national standards, covering all relevant structural actions. The program calculated key responses such as moment capacity, shear force distribution, support reactions, and displacement under load. Manual calculations were then conducted to determine the required reinforcement, referencing code provisions for flexural strength, minimum reinforcement ratio, and bar spacing. Both primary (longitudinal) and secondary (transverse) reinforcement were designed, considering placement feasibility and structural efficiency. The total required steel area was also translated into reinforcement weight per unit area (kg/m²), while concrete volume per square meter and slab self-weight were computed to assess material consumption. These results were interpreted from both a structural safety and environmental sustainability standpoint. By comparing design alternatives, the study was able to recommend slab and reinforcement configurations that optimize material use while maintaining code compliance and climate resilience. The analysis thereby provided a technical foundation for bridge designs that are not only structurally sound but also environmentally responsive.

RESULT AND DISCUSSIONS

Structural Response of Slab Elements under Combined Loads
The finite element simulation conducted in SAP2000 provided a comprehensive analysis of the behavior of the sidewalk and deck slabs under load combinations as defined in SNI 1725:2016. The sidewalk slab, which predominantly bears pedestrian and finishing loads, showed a maximum mid-span bending moment of 10.87 kNm and maximum shear force of 14.42 kN. Meanwhile, the deck slab, which carries vehicular loads, exhibited a higher structural demand, with a peak moment of 28.35 kNm and a shear force of 22.16 kN. Both components were evaluated for serviceability through deflection analysis. The maximum mid-span deflections were 4.8 mm for the sidewalk and 8.2 mm for the deck slab, which are below the allowable limit set by L/800. These findings affirm the structural adequacy of the slabs under combined loading.

Table 1. Structural Result from SAP2000 Simulation

Component	Max. Bending Moment (kNm)	Max. Shear Force (kN)	Max. Deflection (mm)	Deflection Limit (L/800)
Sidewalk Slab	10,87	14,42	4,8	Compliant
Vehicle Deck Slab	28,35	22,16	8,2	Compliant

Reinforcement Detailing, Code Verification, and Crack Control

Based on the structural demands, reinforcement detailing was performed using the provisions of SNI T-12-2004 and SNI 2847:2013. For the sidewalk slab (50 cm thickness), the design used D16 bars spaced at 128 mm longitudinally and D13 bars at 210 mm transversely. The deck slab (20 cm thickness) used D16 at 180 mm for primary reinforcement and D13 at 225 mm for secondary reinforcement. These configurations were chosen based on structural adequacy and crack control.

Table 2. Reinforcement Details of Slab Components

Component	Slab Thickness	Main Reinforcement	Distribution Reinforcement	Area of Steel (As, cm^2/m)	Design code Reference
Sidewalk Slab	50	D16 @ 128 mm spacing	D13 @ 210 mm spacing	2,01	SNI T-12-2004
Vehicle Deck Slab	20	D16 @ 180 mm spacing	D13 @ 225 mm spacing	1,51	SNI T-12-2004

Material Efficiency and Sustainability Assessment

In support of sustainability assessment, the study evaluated material efficiency through parameters such as total steel consumption, concrete volume, and self-weight of slabs. The sidewalk slab required 32.1 kg/m^2 of steel and 0.50 m^3/m^2 of concrete, whereas the deck slab required 21.5 kg/m^2 of steel and 0.20 m^3/m^2 of concrete. The self-weight for the two slabs was 12.5 kN/m^2 and 5.0 kN/m^2 respectively, confirming that the deck slab design was more efficient in terms of material use.

Table 3. Material Efficiency Evaluation

Component	Steel Weight (kg/m^2)	Concrete Volume (m^3/m^2)	Self-Weight (kN/m^2)
Sidewalk Slab	32,1	0,50	12,5
Vehicle Deck Slab	21,5	0,20	5,0

Environmental Loading Resistance: Wind and Temperature Effects

In tropical regions, bridges are exposed to high thermal and wind stresses. Simulated temperature changes ($\Delta T = \pm 15°C$) induced stress responses of 0.96 MPa in the sidewalk and 1.23 MPa in the deck slab—both within safe ranges for concrete. Lateral displacements caused by wind pressure were minor, at 0.8 mm and 1.1 mm respectively.

Table 4. Structural Response to Thermal and Wind Loads

Component	Temperature Change (ΔT, °C)	Thermal Stress (MPa)	Additional Deflection (mm)
Sidewalk Slab	±15	0,96	0,8
Vehicle Deck Slab	±15	1,23	1,1

Structural Safety Validation against SNI Criteria

To ensure compliance with safety standards, the calculated flexural capacities (Mu) were compared with required demand (Mu_req). The sidewalk slab had a Mu of 15.2 kNm (vs 10.87 kNm required), and the deck slab had 34.7 kNm (vs 28.35 kNm required), yielding safety ratios of 1.40 and 1.22 respectively. Deflections and reinforcement areas were also within acceptable limits.

Table 5. Performance Validation Against SNI Requirements

Component	Mu (kNm)	Required Mu (kNm)	Mu/Mu_req Ratio	Actual Deflection (mm)	SNI Deflection Limit (mm)
Sidewalk Slab	15,2	10,87	1,40	4,8	6,25
Vehicle Deck Slab	34,7	28,35	1,22	8,2	10,00

Discussion

This research confirms that both sidewalk and vehicle deck slabs in a composite bridge design can achieve structurally efficient outcomes when reinforcement is configured to meet precise demand, with safety factors exceeding standard thresholds and deflection remaining within acceptable service limits. The reinforcement strategy implemented here using D16 and D13 bars provided not only structural adequacy but also material efficiency, contributing to lean construction without compromising safety. These results are in line with previous findings that emphasize the role of optimization in reinforced concrete systems for sustainability purposes, [35] although this study differs by focusing on slab elements and their interaction with local design codes under tropical conditions. The deck slab's lower consumption of steel (21.5 kg/m²) and concrete (0.20 m³/m²) demonstrates that efficient cross-sectional design can reduce both structural weight and environmental burden, complementing sustainability. In terms of environmental loads, the applied thermal variations induced stresses well within the material's elastic capacity regarding temperature-sensitive infrastructure in tropical zones. The use of a simulation-driven design process integrated with SNI code provisions can be adopted as a practical strategy for engineers working on region-specific infrastructure in developing countries. In addition, the outcomes of this study can be used by transportation authorities to guide updates to national bridge design standards, particularly in the incorporation of climatic load factors at the component level. This approach contributes not only to safer and more durable bridges but also supports national efforts in achieving the Sustainable Development Goals (SDGs), especially in climate-responsive infrastructure planning. Moreover, the framework proposed in this study offers replicable guidance for future studies addressing the long-term sustainability of small-to-medium span bridge elements in high-risk environments.

Limitation and Suggestion for Future Research

Despite the insights gained in this study, some limitations must be recognized. Primarily, the structural analysis focused solely on static load combinations derived from SNI 1725:2016 and did not account for dynamic influences such as traffic loading cycles, seismic activity, or fatigue over time. Additionally, although thermal and wind effects were simulated, other environmental challenges typical of tropical climates—like heavy rainfall, prolonged humidity, and flood erosion—were outside the scope of this analysis. The environmental evaluation was also limited to material quantity indicators and did not include a full life cycle environmental assessment. To address these limitations, future research should consider modeling bridge components under dynamic and long-term environmental stress, including deterioration mechanisms such as corrosion and cracking due to moisture infiltration. Coupling the analysis with field data or experimental validation will enhance the credibility of the simulation results. Moreover, integrating life cycle assessment (LCA) and multi-objective optimization into the early design process could further align structural efficiency with sustainability goals. Expanding this framework to different bridge types and span categories across diverse geographic settings would also strengthen its generalizability and impact in real-world applications.

CONCLUSION

This study has successfully evaluated the structural performance and material efficiency of sidewalk and vehicle deck slabs in a steel–concrete composite bridge system using SAP2000 simulation integrated with Indonesian national standards (SNI 1725:2016, SNI T-12-2004, and SNI 2847:2013). The results demonstrated that both slabs met strength and serviceability requirements, with moment capacity ratios exceeding 1.2 and deflections remaining within acceptable limits. Reinforcement detailing using D16 and D13 bars yielded efficient configurations that minimized overdesign while maintaining compliance with code provisions. Additionally, the deck slab showed superior material performance, requiring only 21.5 kg/m^2 of steel and 0.20 m^3/m^2 of concrete, contributing to lighter dead loads and reduced environmental impact. Thermal and wind load simulations confirmed the slabs' structural resilience under tropical climate conditions, with induced stresses and displacements remaining within safe thresholds. These findings not only validate the feasibility of using detailed simulation to optimize component-level bridge elements but also highlight the importance of incorporating environmental loads early in the design process. The study contributes practically by offering a replicable methodology for engineers designing infrastructure in climate-sensitive regions, and academically by filling a research gap on slab-level design integration in tropical contexts. Furthermore, the results support sustainable infrastructure development aligned with SDG 9 and SDG 13, emphasizing the relevance of adaptive, material-efficient bridge design for future climate-resilient transport systems.

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AUTHORS CONTIBUTIONS

Randy Setiawan conceptualized the study, supervised the research process, and ensured the integration of structural and environmental aspects throughout the project. Priska Cahya Larasati was responsible for structural modeling, SAP2000 simulation, and preliminary data analysis. Viktorgius conducted reinforcement detailing based on national codes and contributed to the interpretation of design validation and supported the preparation of graphical materials, assisted in data tabulation, and contributed to the revision. Rizky Ananda Putra carried out the literature review, environmental performance assessment, and contributed to drafting the results and discussion. Janne Hillary formatting of the manuscript. All authors read, revised, and approved the final version of the manuscript prior to submission.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors confirm that they have participated voluntarily, with no conflict of interest in the design, execution, or publication of this research.

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